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Evaluation of the long-term environmental performance of Greek lignite-fired power stations

J.K. Kaldellis [*,1], M. Kapsali [1]

Lab of Soft Energy Applications & Environmental Protection, TEI of Piraeus, P.O. Box 41046, Athens 12201, Greece

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ABSTRACT

At national, regional and global level, there is no doubt that the electric generation from fossil fuel-fired power plants is one of the greatest causes of air pollution and climate change. However, fossil fuels contribute more than 70% in the planet electricity generation during the last 30 years. In Greece, lignite is the only proved significant indigenous fossil fuel source, currently representing about 50% of the national electricity generation (a situation which is not expected to change dramatically in the near future). As a result, owed to the use of local lignite reserves (poor quality lignite), the Greek Lignite Thermal Power Stations (LTPSs) are responsible for the production of significant airborne emissions and particle releases (e.g. CO_2, SO_2, NO_X, PM). At the same time, Greece, on top of the Kyoto Protocol, has accepted specific obligations and incorporated into its national legislation several air quality Directives concerning the reduction of various harmful gases and particle releases attributed to fossil fuel combustion. Thus, wide scrutiny of concentration time series of all these airborne emissions constitutes an important indicator of the current technology used, considering at the same time that any violation noted should be the object of serious national concern. Under this argument, the current work presents and evaluates the long-term environmental performance of the Greek lignite-based electricity generation system as far as CO_2, NO_X, SO_2 and PM are concerned up to the year 2011. According to the results obtained, one may rank the operating LTPSs according to their environmental performance giving to the Greek society the necessary tools to determine their utilisation factor on top of the techno-economic criteria used up to now.

Contents

* Corresponding author.
E-mail address: jkald@teipir.gr (J.K. Kaldellis).
URL: http://www.sealab.gr (J.K. Kaldellis).
[1] Tel.: + 30 210 5381237, Fax.: + 30 210 5381467.

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1. Introduction

The role of energy in the social and economic progress of mankind is of unquestionable value, but beyond that, it is also an essential part of our daily life. Population and income growth are the two most powerful driving forces behind the demand for energy. Since 1900, our planet population has more than quadrupled and real income has grown by a factor of 25. World primary energy consumption grew by 45% over the past 20 years and is expected to keep growing by 40% over the next 20 years [1]. Electricity generation is the fastest and largest growing source of world energy demand, greater than the primary energy used in both the transportation and the residential–commercial sector. For the time being, fossil fuels (coal, oil and natural gas) continue to dominate in the world's electricity generation sector (Fig. 1) but their consumption presents large variations from country to country, depending on the available domestic resources and national energy policies.

Unfortunately, this strong long-term dependence on fossil fuel combustion for energy production has caused several environmental problems, such as greenhouse gas (GHG) accumulation, acidification, air pollution, water pollution, damage to land surface and increase of ground-level ozone, which have a huge impact on present and future generations' health [2,3]. Among fossil fuels, coal (hard coal and lignite, i.e. principal fuel sources used for electricity generation) is considered to be the largest contributor to the human-made increase of CO_2 in the atmosphere. Furthermore, combustion of coal is responsible for significant air pollutant releases, such as sulphur oxides (mainly sulphur dioxide), various oxides of nitrogen and fine particles, with the abatement of these emissions comprising a common environmental issue of the international agenda [4].

Annual world production of lignite decreased by 5.5% in 2009, to about 915 million tons. Following its 1989 peak, lignite production declined steadily until 1999, largely owed to supply and demand problems in central and Eastern Europe. Since then, production has been fairly stable, close to the production levels of 2009. It should be noted that hard coal and lignite currently represent approximately 80% of EU's fossil fuel reserves, while approximately 30% of electricity generation in the EU-27 is coal-based (11% from lignite and 19% from hard coal). In several countries across Europe (e.g. Greece, Serbia) lignite accounts for a significant percentage of total power generation (i.e. more than 50%) (see Fig. 2) [5], with many of these nations featuring amongst the top lignite producing countries in the world. Finally, it should be noted that Europe – where lignite represents an energy resource of key importance – is responsible for around 50% of the respective world production [6].

In Greece, lignite is the only proved significant indigenous fossil fuel source, representing more than 50% of the national (interconnected) electricity generation (Figs. 1 and 2), making the country the second lignite producer in the EU and the fifth in the world, based on the mining of more than 60 Mt on an annual basis. However, although electricity production from natural gas and renewable forms of energy has increased during the recent years, dominant role of lignite is not expected to change dramatically in the near future. At the same time, Greece – as an EU Member State –, on top of the Kyoto Protocol, has accepted specific obligations and incorporated into its national legislation several air quality Directives concerning the reduction of various harmful gases [7] and particle releases attributed to fossil fuel combustion. This legislative framework, apart from setting threshold values for measuring and assessing ambient air quality, it also defines, among others, the number and location of sampling points as well as the measuring and reference methodologies for each flue gas. In this context, the Greek Public Power Corporation (PPC) (i.e. the exclusive supplier and practically the sole producer of energy deriving from lignite combustion) contributes to the monitoring of ambient air quality in the vicinity of the thermal power plants under its operation, with numerous measuring stations performing systematical air quality measurements.

To this end, the national levels of harmful gases emitted and particles released from the thermal power plants as a by-product of lignite combustion, constitute an important indicator of the current technology used, as well as of the compliance of the State with its commitments under the corresponding environmental legislation. Thus, as it may be easily concluded, wide scrutiny of concentration time series of all these harmful gases and particle releases is of great importance, considering at the same time that any violation noted should be the object of serious national concern. Under this argument, considering the leading role that lignite has been playing in the national electricity sector [8] until today – and will continue to do so in the foreseeable future – the current work presents and evaluates the long-term environmental

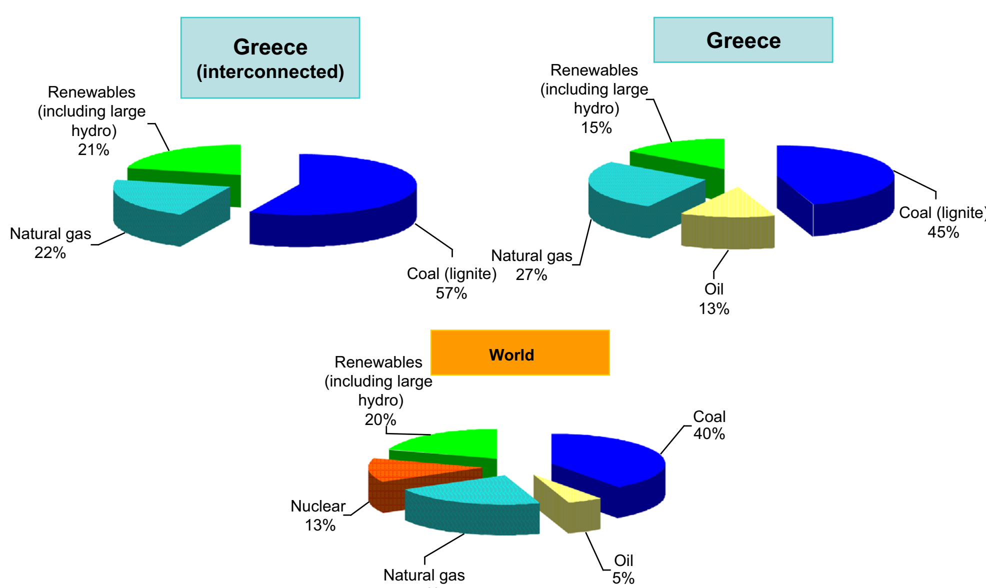

Fig. 1. Sources of electricity generation as for January 2011.

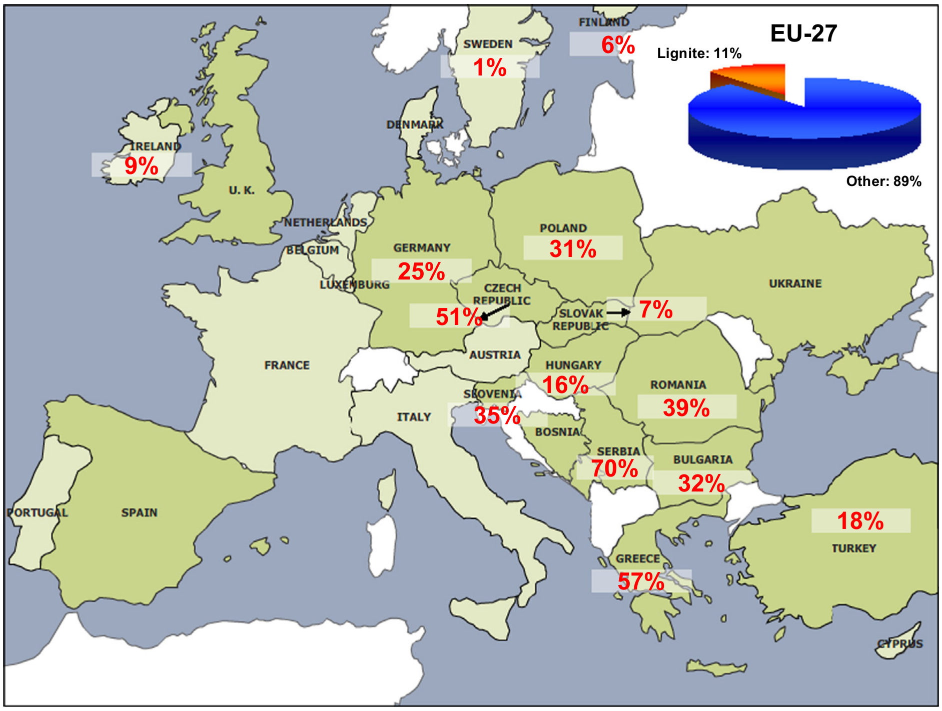

Fig. 2. The role of lignite in power generation in several European countries. Based on data from [5].

performance of the Greek lignite-based electricity generation system as far as CO_2, NO_X, SO_2 and PM (or PM_{total}, referring to total particular matter emissions) are concerned from the first year that reliable data exist (i.e. 1995) up to the year 2011 for which official data are available.

2. Brief presentation of the Greek electricity generation system

The national Electricity Generation System (EGS) is divided into two main categories, i.e. the so-called interconnected system of the mainland and the autonomous power plants of the Aegean Archipelago islands. Concerning the Archipelago region, the Greek EGS is composed of approximately 40 local Autonomous Power Stations (APSs) which consume imported fuel amounts of diesel and heavy oil [9]. On the other hand, the mainland's electrical grid, on top of large hydro installations (3.1 GW), is mainly supported by Thermal Power Stations (TPSs) of total rated power 8.2 GW, with most of them being based on indigenous lignite consumption. Lignite power units produced 30.5 TWh_e in 2009 and 27.6 TWh_e in 2011, while total electricity generation in Greece (including the autonomous islands) was 53.2 TWh_e in 2011. Across the interconnected system (excluding the autonomous islands) the share of lignite electricity generation in 2011 was about 57%, the share of natural gas 22%, while the share of renewables (mainly large hydro) was about 21% (see also Fig. 1).

Fig. 3, illustrates the location of major power plants all over Greece. As seen in the map, operation of the existing electricity generation units in the Greek mainland is mainly based on local lignite reserves, while the capacity share for natural gas, along with the combined cycle stations, is slightly below 3 GW. Actually, lignite represents the exclusive fuel source for six major PPC-owned power stations which comprise 20 generating units with a total installed capacity of 5.3 GW (Table 1).

At this point, it should be mentioned that the Greek exploitable lignite reserves (Fig. 3) are among the poorest fossil fuels used in thermal power plants all over Europe with very low calorific value and a tendency to degrade more in recent years because of the intensive exploitation of existing mines [10]. In fact, as it may be seen in Fig. 4, indigenous lignite reserves present the minimum calorific value among European countries, with their quality however oscillating highly both within and across mines. In this context, by taking into consideration the physical characteristics of the lignite used in TPSs, the lowest calorific values are found in the areas of Megalopolis and Drama (3770 to 5020 kJ/kg) and Ptolemais-Amynteon (5230 to 6280 kJ/kg). In Florina and Elassona the calorific value lies between 7540 and 9630 kJ/kg. The ash content ranges from 15% (Ptolemais) to 19% (Elassona) and the moisture content from 41% (Elassona) to 58% (Megalopolis). The sulphur content is generally low in the mines of Western Macedonia-Northern Greece, while in Megalopolis and Florina areas it is around 1%, which means that in combination with the existing low level of calcium oxide (i.e. a desulphurising agent), combustion of local reserves requires desulphurisation [11].

Greece possesses lignite resources of 5 billion tons, of which 3.1 billion tons are exploitable reserves suitable for electricity generation. The most important deposits have an average total depth of 150–200 m (comprising layers of lignite alternating with layers of soil) and are located in the northern part of the country, at Ptolemais-Amynteon and Florina (1.5 billion tons), at Drama (900 million tons) and at Elassona (170 million tons), as well as in the south, at the Megalopolis region (225 million tons) (Fig. 3). Furthermore, apart from lignite deposits, there is also a large peat deposit of about 4 billion cubic metres at Philippi (North Greece-Eastern Macedonia).

3. Analysis of national emissions

3.1. Total emissions-time evolution and binding limits

3.1.1. CO_2

When GHG emissions are considered, CO_2 comprises the principal gas which receives the most attention for its greenhouse effect among other gases, such as methane, nitrous oxide and the

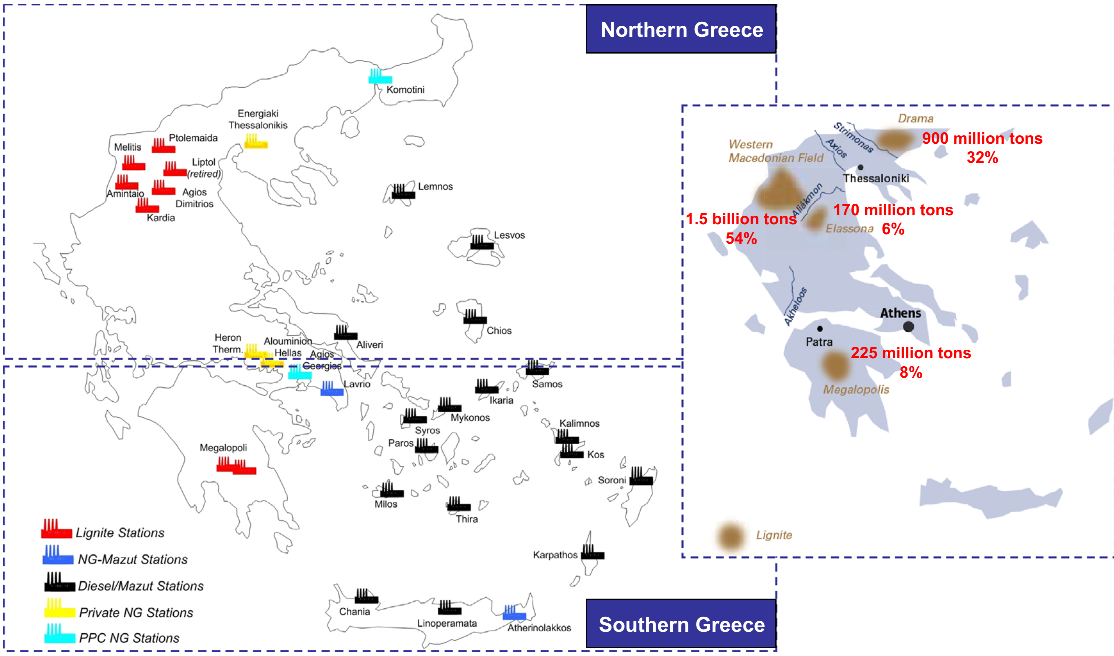

Fig. 3. (Left) Greek thermal and natural gas power stations and (Right) location of main Greek exploitable lignite reserves.

Table 1
Basic characteristics of major Greek thermal power stations.

j	TPS/unit	Installed capacity (MW)	Start-up operation	Fuel	Location	Technical characteristics
1	Ptolemaida I[a]	70	1959	Lignite	North Greece	Boiler supplier: KSG, Stein, EVT
	Ptolemaida II	125	1962		Kozani, W. Macedonia	T/G supplier: Alsthom, BBC
	Ptolemaida III	125	1965			
	Ptolemaida IV	300	1973			
2	Megalopolis-A I	125	1970	Lignite, bituminous coal	South Greece	Boiler supplier: Vereinigte Kesselwerke
	Megalopolis-A II	125	1970		Arcadia, Peloponnesus	T/G supplier: AEG, Siemens
	Megalopolis-A III	300	1975			
	Megalopolis-B IV	300	1991			
3	Kardia I	300	1975	Lignite	North Greece	Boiler supplier: Stein, Ganz-Rock, T/G supplier: Alsthom, LMZ,
	Kardia II	300	1975			
	Kardia III	325	1980		Kozani, W. Macedonia	Teploenergo, EPC: Zarubezhenergoproekt
	Kardia IV	325	1981			
4	Ag. Dimitrios I	300	1984	Lignite	North Greece	Boiler supplier: Stein, EVT, Biro T/G supplier: Alsthom, LMZ, Electrosila, Ansaldo
	Ag. Dimitrios II	300	1984		Kozani, W. Macedonia	
	Ag. Dimitrios III	310	1985			
	Ag. Dimitrios IV	310	1986			
	Ag. Dimitrios V	375	1997			
5	Amyntaio I	300	1987	Lignite	North Greece	Boiler supplier: Stein,
	Amyntaio II	300	1987		Florina, NW. Macedonia	T/G supplier: LMZ
6	Florina (Melitis) I	330	2003	Lignite	North Greece	Boiler supplier: Ganzrock
					Florina, NW. Macedonia	T/G supplier: ABB, EPC: ABB

[a] Note that Ptolemaida's I thermal power unit has recently been retired (June 2010).

halocarbons (a group of gases containing fluorine, chlorine and bromine). CO_2 is emitted in large amounts into the atmosphere and has a rather long atmospheric lifetime. When fossil fuels are burned to produce energy the carbon stored in them is emitted almost entirely as CO_2.

CO_2 is emitted by the burning of fossil fuels for electricity generation, industrial uses, transportation, as well as in residential and commercial buildings. In this context, the continuously growing energy demand plays a key role in the upward trend of world CO_2 emissions due to fossil fuel combustion. Generation of electricity and heat is by far the largest contributors, being responsible for more than 40% of world's CO_2 emissions, with coal and peat being the leading sources [12] (see Fig. 5).

Total GHG emissions in the EU-27 stood at 4614.5 million tons of CO_{2-eq} in 2009. This figure marked an overall reduction of 17.4% when compared with 1990 Kyoto's base levels. Since then, a slight but continuous reduction takes place with total GHG emissions, as for 2011, being equal to 4550 million tons. By far the most

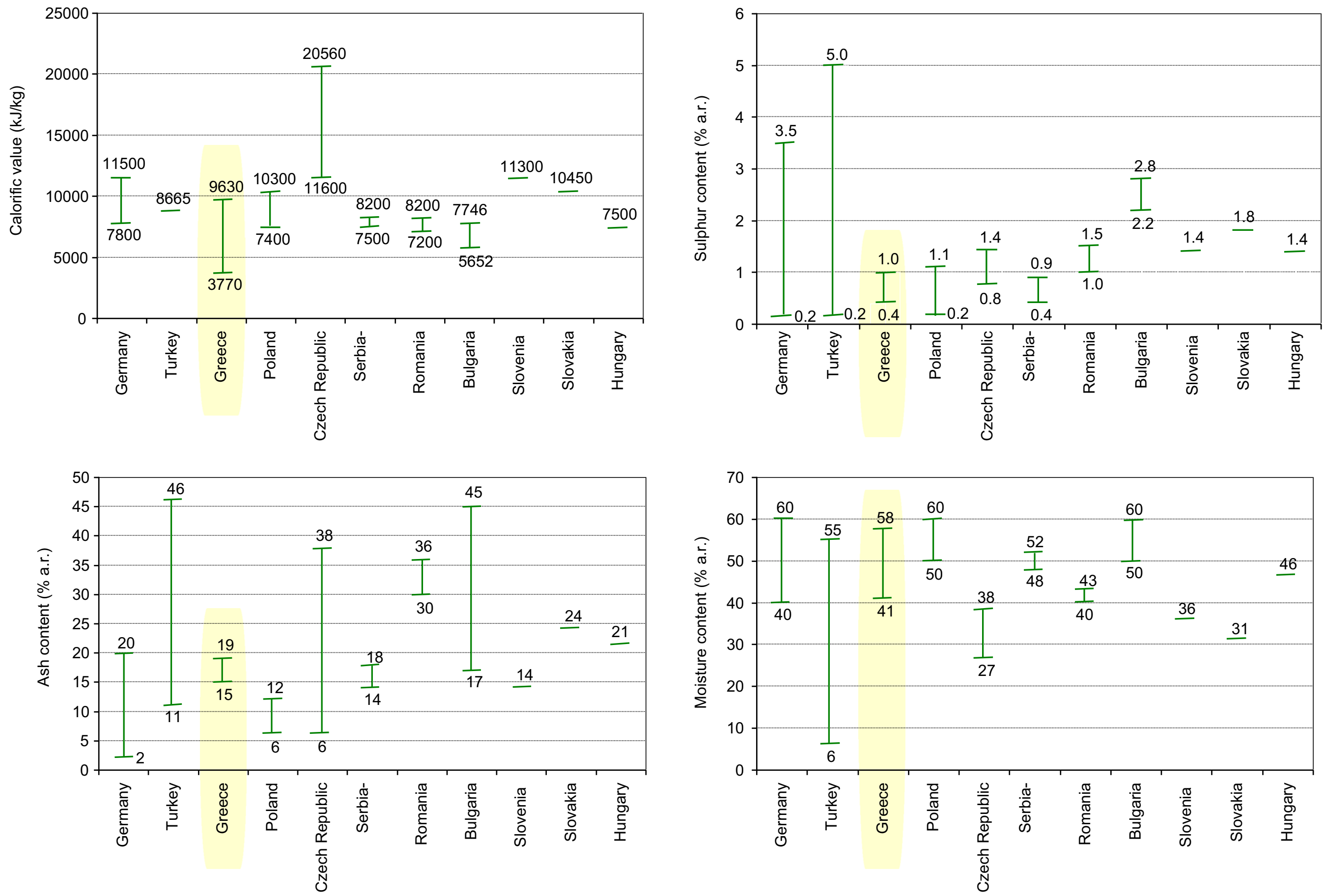

Fig. 4. Maximum and minimum values of main quality characteristics of various exploitable lignite reserves in Europe.

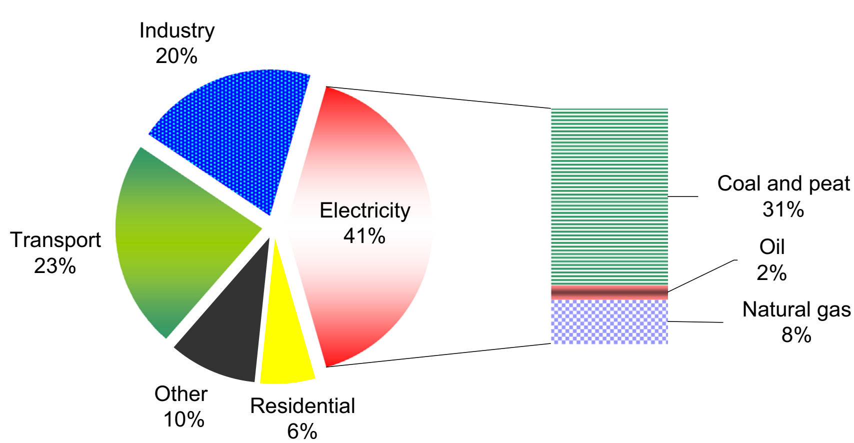

Fig. 5. Sector share in world CO_2 emissions. Based on data from [12].

important source of GHG emissions across Europe is that of fuel combustion, which takes place in energy transformation (i.e. electricity generation), transport and a range of industrial activities [13].

Greece, since ratifying the Kyoto Protocol in May 2002, committed to restrict its national GHG emissions by the year period of 2008–2012 to the levels of +25% in comparison with the respective emission production of the base year 1990. In this context, based on official data [14,15] for the respective time period, the relative increase of national GHG emissions for 2011 is found much lower than the respective +25% limit (~11%) (see also Fig. 6), while the total amount of emissions reaches approximately 115 Mt of CO_{2-eq}. Throughout this period, GHG emissions' profile shows a clear domination of the energy sector, with CO_2 comprising the main GHG. The catalytic contribution of the energy sector (including transport) is demonstrated by a long-term average of about 80%, followed by the industry and the agriculture sectors with 10% and 9% long-term average contribution, respectively.

3.1.2. SO_2 and NO_X

Sulphuric emissions from power generation concern SO_2 and SO_3 which are produced when the sulphur of the solid and liquid fossil fuels is burned. During combustion, sulphur trioxide is

normally transformed to sulphur dioxide and thus the latter represents 99.5% of sulphur oxides in the flue gas. Coal and petroleum products contain sulphur compounds and thus the combustion of these fossil fuels, releases sulphur dioxide. On the other hand, NO_X includes mainly nitric oxide and nitrogen dioxide. Nitrogen oxides, which are responsible for respiratory infections and other serious diseases, as well as for the formation of acid rain, ozone and PM, are produced when nitrogen and oxygen are combined during combustion which takes place in fossil fuel-fired heat and electricity generating plants and in various transportation-related sources (dominated by cars and trucks, but also including trains, ships, airplanes and other non-road vehicles) and processes in chemical plants.

Together with the Kyoto Protocol, Greece, as an EU Member State, has also accepted specific multinational environmental agreements and incorporated into its national legislation several air quality related EU Directives such as the National Emission Ceilings Directive (2001/81/EC). In this context, according to that Directive, all Member States of the EU, including Greece, need to succeed in reducing their annual SO_2 and NO_X emissions. Particularly, Greece is committed (according to the SO_2 and NO_X Protocols) not to exceed the ceiling of 523 kt of SO_2 and 344 kt of NO_X emissions from 2010 onwards. As seen in Fig. 7, although this is not the case for most of the years during the 1990–2011 time period for both acidifying substances, during the last years Greece is in compliance with the frame specified in the Protocols, since the respective emissions are well below the ceilings.

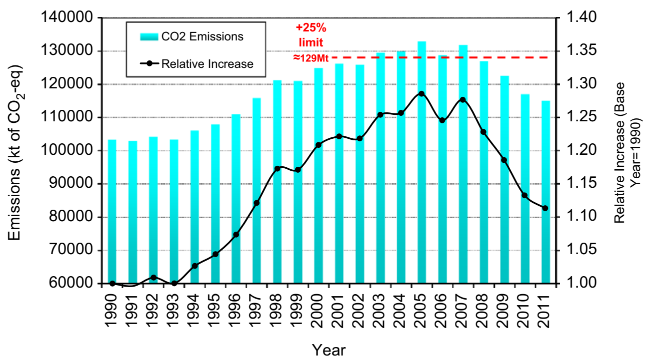

Fig. 6. Time evolution of CO_{2-eq} emissions in Greece and relative increase in relation to the base year 1990.

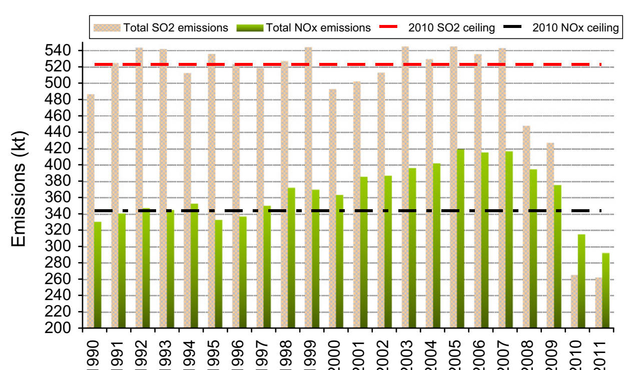

Fig. 7. Total Greek SO_2 and NO_X emissions compared with 2010 national emission ceilings. Based on data from [16].

In fact, as far as SO_2 is concerned, the above ceiling target was achieved in 2008 (with 448 kt), a situation which has been maintained until today (emissions are close to 260 kt during the last 2 years) [16] (Fig. 7) not only because of the measures taken (e.g. operation of desulphurisation units at large thermal power plants, increasing share of renewables, reductions with respect to the sulphur content of liquid fossil fuels, increasing share of natural gas in the Greek energy mix) but mainly as a consequence of energy demand decrease due to the intense economic crisis Greece is suffering from. At this point it is worth mentioning that since the world economic crisis of 2008, total electricity generation in Greece has dropped by more than 10% while on the other hand, electricity generation from renewables (including large hydro) has increased by 40% (i.e. from almost 5.7 TWh_e in 2008 to about 8 TWh_e in 2011).

Similar considerations apply also for NO_X production. As seen in Fig. 7, average nitrogen oxides emissions for the time period 1990–2009 were fairly above the EU emission ceiling, with the maximum annual NO_X production being recorded in 2005 (i.e. 420 kt). Furthermore, one should not disregard that after 1999 the NO_X production increased gradually, despite the introduction of natural gas in the local market. However, during the last years (2010 and 2011) the respective emissions have significantly dropped mainly due to measures taken in the transport sector (e.g. passenger cars withdrawal programme) and the decrease of electricity production.

Indisputably, the biggest source responsible for about 85% of SO_2 emissions in Greece is by far the energy sector (Fig. 8), including heat and electricity generation as well as combustion processes used in the manufacturing industry [17]. The energy sector is also responsible for quite more than one half of national NO_X emissions, while the remaining is emitted mainly by the road transportation sector (see Fig. 8) [17,18].

3.1.3. PM

PM is an air pollutant consisting of a mixture of solid and liquid particles suspended in the air. These particles differ in their physical properties (e.g. size, chemical composition, etc). PM can either be directly emitted into the air (primary PM) or formed secondarily in the atmosphere from gaseous precursors (mainly sulphur dioxide, nitrogen oxides, ammonia and non-methane volatile organic compounds). Main sources of PM are anthropogenic activities such as the burning of fossil fuels in vehicles,

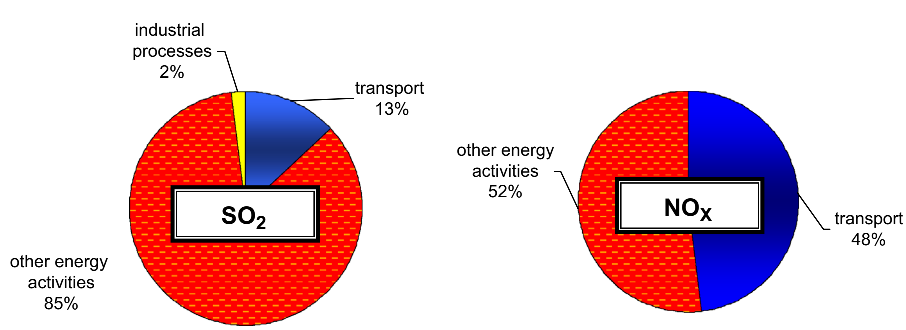

Fig. 8. Breakdown of national SO_2 and NO_X emissions by sector. Based on data from [17].

power plants and various industrial processes or natural phenomena such as dust storm events that contribute in increased concentrations [19]. Atmospheric particles have a basic role in atmospheric chemistry, human health and climate. Investigations have shown that there is a correlation between PM (especially fine and ultrafine particles) and health effect [20] and for this purpose PM is typically defined by size, with the smaller particles having the most severe health impact. Commonly quoted values for PM are Total Particulate Matter (TPM) or Total Suspended Particles (TSP), particles with a diameter of less than 10 μm (PM_{10}) and particles with a diameter of less than 2.5 μm ($PM_{2.5}$). As resulting from the above, the effects of PM ambient air concentrations, its consequences on health and its safe limit value for the population have become issues of great international concern. However, since an important mass fraction of TSP comprises of non-inhalable particles with a less severe impact on health, the monitoring of TSP now focuses on PM_{10} (particles of less than 10 μm aerodynamic diameter).

In Greece, energy-related PM emissions (i.e. aggregated primary and secondary PM_{10}) increased by 19% between 1990 and 2007. In 2007, "energy supply" (i.e. energy industries and fugitive emissions from fuels) and "transport" (i.e. emissions from road and off-road sources such as aviation and marine) represented the sectors with the highest PM emissions in Greece (53% and 22% of the total PM emissions, respectively), see Fig. 9. The majority of the increase in emissions of energy-related particulate matter pollutants between 1990 and 2007 is attributed to the "energy supply" sector, while emissions from other sectors ("industry" i.e. emissions from combustion processes used in the manufacturing industry including boilers, gas-turbines and stationary engines as well as emissions from construction, "other (energy-related)" i.e. emissions from the household sector, "non-energy" i.e. emissions from industrial processes, waste and agriculture) remained almost stagnated during this time period. Furthermore, as seen in Fig. 9, PM emissions from "transport" were almost stable between 1990 and 2007, despite the increasing number of vehicles [21,22]. This is attributed to the substitution of old technology vehicles by new catalytic ones.

Council Directive 1999/30/EC (Annex III) introduced the current binding limit values for PM_{10} concentrations (40 μg/m^3 as the annual average and 50 μg/m^3 as the daily average not to be exceeded for more than 35 days during a calendar year). It should be noted that, after the announcement of the Directive, results from long-term monitoring of PM concentrations [23–25], apart from problems with regulatory compliance due to violation of the imposed limits, indicated the existence of a serious national pollution problem [26]. More precisely, according to recent data [27], PM emissions present extensive violations in many cities around the country, e.g. Athens, Thessaloniki and areas where the major power plants are located. Twenty four hour averaged PM_{10} concentrations at the greater Athens area reveal a substantially higher number of days, than the allowed of 35 days per year, for which the concentrations exceeded the threshold of 50 μg/m^3. Moreover, the annual mean concentrations in the same area are well above the threshold limit of 40 μg/m^3. Similarly, the situation in Thessaloniki (i.e. the second-largest city in Greece and the capital of the region of Central Macedonia) is equally disappointing, ranking the city among the most polluted in Europe regarding PM_{10}.

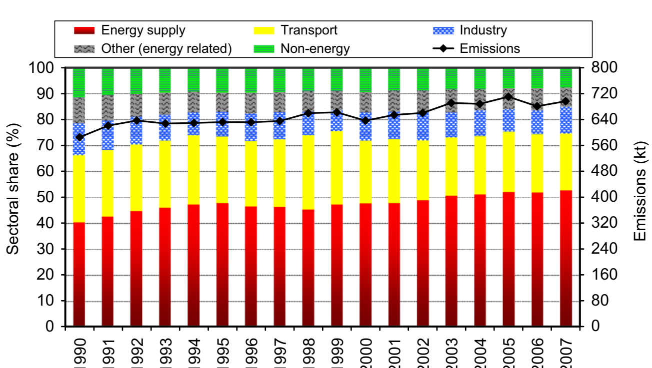

Fig. 9. Total annual energy-related emissions of PM and sectoral shares. Based on data from [21,22].

3.2. Emissions per lignite thermal power station (LTPS)

3.2.1. CO_2

As already mentioned, coal combustion is the largest contributor to the human-derived CO_2 in the air. In Greece, approximately 35% of the annual CO_2 emissions, i.e. 40 Mt of a total of about 120 Mt of CO_{2-eq}, derive from coal (lignite) combustion for electricity production. In fact, although total CO_2 emissions present a slight decreasing trend (see also Fig. 6) in the last few years (currently being about more than 10% less than the respective in 2005) as a result of the country's commitment to meet its Kyoto targets as well as due to reduction of electricity demand (owing to economic recession), only a limited part of this reduction can be attributed to effective measures adopted in the lignite-based electricity generation sector.

Particularly, as one may see in Fig. 10, total CO_2 production from the major Lignite Thermal Power Stations (LTPSs) almost coincides with the variation in electricity generation, while being slightly reduced (mainly due to lignite-based electricity consumption decrease) from 43 Mt in 2005 (comprising the year that the first phase (2005–2007) of the National Allocation Plan (NAP) was launched [28]) to about 40 Mt after 6 years (in 2011). This slight reduction also reveals the limited application – up till now – of drastic measures for CO_2 emission reduction from the Greek lignite-based electricity generation sector. In this context, the largest of PPC′s lignite-fired power plants (producing more than 80% of the nation's lignite-based electricity), all located in northern Greece (in the region of Western Macedonia (see also Table 1)), account for 85% of the total annual CO_2 emissions from the Greek lignite-based electricity generation sector. Also, at this point, it should be noted that almost all PPC's LTPSs are not in a compliance status with the obligations of the country in regard to the EU Emissions Trading Scheme (ETS). In fact, concerning the year 2011 (second NAP phase (i.e. 2008–2012)), for which official data are available [29], almost all PPC's LTPSs violated their allowances, with the largest TPS of Ag. Dimitrios (which covers about 35% of the country's electricity needs) presenting the greatest emission excess, i.e. about 3200 kt/year more than permitted (verified data for 2011) [28].

3.2.2. SO_2 and NO_X

The impact of the electricity sector on national flue gas emissions (especially SO_2) is mainly caused by the continued reliance on the poor quality indigenous lignite. The 5.3 GW installed capacity of the lignite-fired power plants represents roughly 40% of the national installed capacity, and it is responsible for about 35% of SO_2 national emissions. On the other hand, NO_X emissions from PPC's lignite-fired power plants seem rather low (currently representing almost 10% of total NO_X emissions) mainly due to the fact that the Greek lignite is poorer (lower calorific value) than other lignite deposits around the world, resulting in even lower combustion temperatures which discourage the production of NO_X.

In this context, by taking into consideration previous studies [30,31] examining SO_2 emissions from 1995 to 2002, along with

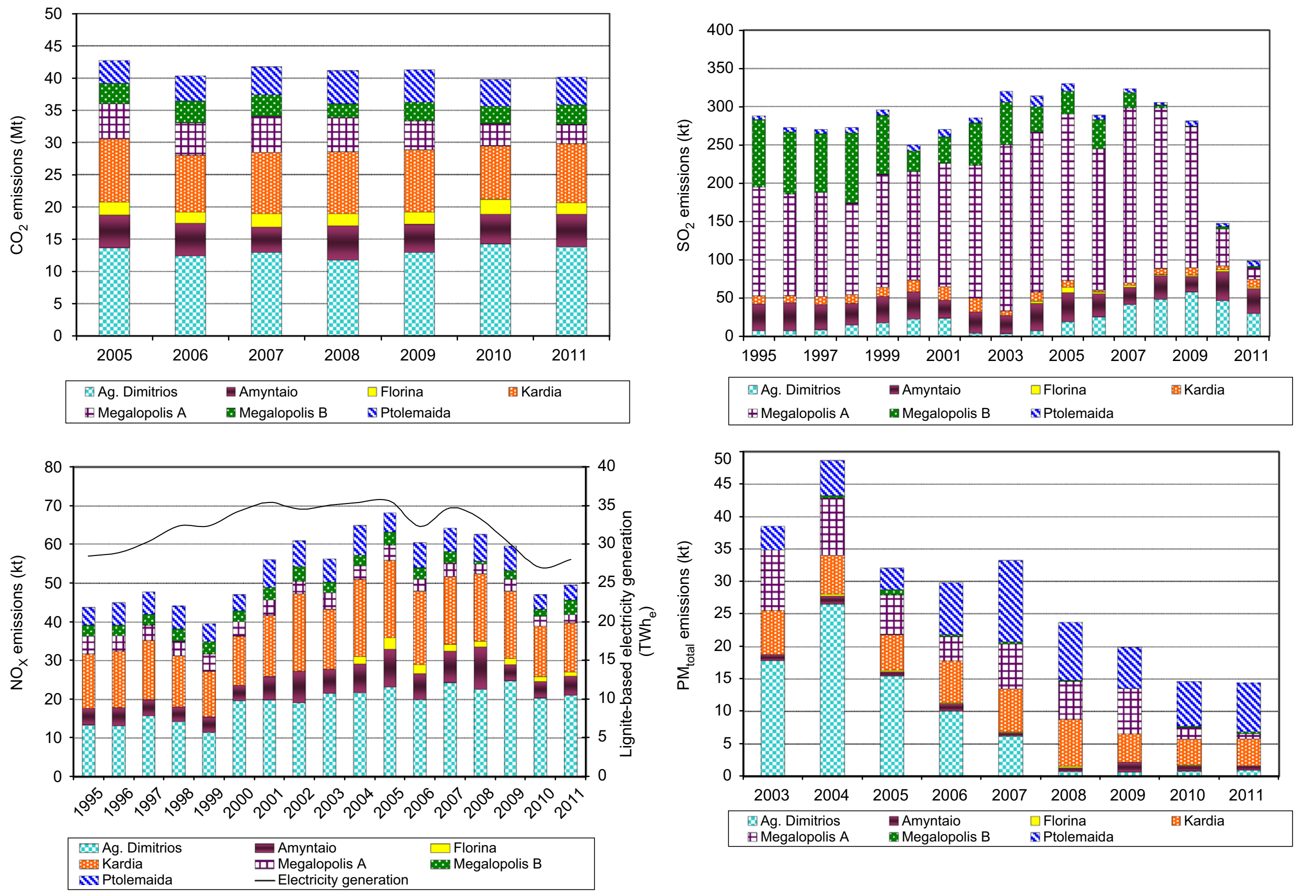

Fig. 10. Time evolution of the Greek LTPSs' emissions.

additional data provided by Greek authorities [32] until 2011, one may observe the time evolution of SO_2 emissions per LTPS in Fig. 10. To this end, comparing northern Greek LTPSs with the southern ones it becomes clear that the contribution of the latter is significantly greater, mainly due to the usage of lower quality lignite with higher sulphur content and relatively low alkaline (CaO) ash content, resulting in generally higher SO_2 emissions. Furthermore, as it may be seen from Fig. 10, the operation of flue gas desulphurisation units after 1999 at large installations for electricity generation, such as Megalopolis B TPS, resulted in a slight temporal restriction of the increase of SO_2 emissions. In fact, the TPSs which have already been equipped with a flue gas desulphurisation unit are: Megalopolis B TPS (Unit IV) in 1999 with further upgrading in 2008, Florina TPS in 2004 and more recently, Megalopolis A TPS (Unit III) by the end of 2009 [33]. It should be noted that the installation of the flue gas desulphurisation unit in Megalopolis A TPS resulted in significant restriction of total SO_2 emissions from lignite-based power generation, as this station was responsible for the noteworthy emission percentage of about 80% since 2009 (see Fig. 10).

Subsequently, the time evolution of NO_X emissions per LTPS is also presented in Fig. 10, by taking into account previous data [34] examining the NO_X emissions from 1995 to 2002, along with more recent ones until 2011 [32]. It is worth mentioning that while in the case of SO_2 emissions values fluctuate between 250 and 330 kt during the time period analysed (excluding the years 2010–2011 where a drastic reduction took place) – mainly due to variation in the quality of the lignite used – for the NO_X emissions there has been a gradual but significant increase over the years (up to the year 2005). However, as one may observe from Fig. 10, things seem to change recently. In fact, the depicted reduction of lignite-based electricity demand in combination with the adoption of some effective abatement techniques resulted in 20% decrease of annual NO_X emissions in 2010 (in comparison with the previous year) while the situation in 2011 almost remained constant. Furthermore, it should be noted that by comparing southern Greek LTPSs with the northern ones it becomes clear that the contribution of the latter is significantly greater, with the two biggest national LTPSs (i.e. Ag. Dimitrios, 1595 MW and Kardia, 1250 MW) being together responsible for more than 70% of the total NO_X annual release (due to lignite combustion) in the country.

3.2.3. PM

In contrast to CO_2 and SO_2 emissions, when analysing the sources of national PM emissions, large lignite-based power plants cannot be considered as the main contributors. As seen in Fig. 10, PM total production from major LTPSs has decreased significantly and is currently of the order of 15 kt/year (representing almost 5% of the total energy-related PM emissions), with the main contributors being those of Ptolemaida's and Kardia's power plants, both producing 75% of the total PM annual release (due to lignite combustion) in the country.

However, it should be kept in mind that although a general downward trend of PM emission levels can be observed (Fig. 10) allegedly due to improvement of filter technology and electricity demand reduction, this cannot be indicative of the application of an effective PM abatement policy. This is because measurements concern cumulative particle quantities and they do not refer separately to the most health-threatening particles such as PM_{10} and $PM_{2.5}$, which – up till now – are determined based on expert judgement and the usage of appropriate indicators. Furthermore,

one should not disregard that, on top of by-products of lignite combustion (directly related to the ash content of the fuel and to the firing configuration of the boiler), significant particle concentrations are encountered from lignite mining operations in the areas surrounding these activities [35]. In this context, the problem becomes even worse and more complicated, especially for urban areas located not far from these activities, due to additional contribution from the urban anthropogenic and natural pollution sources [36].

4. Discussion

4.1. Analysis of emission factors per LTPS

Based on the above presented official data concerning national emissions, it is now possible to estimate the specific emission factor of every major Greek LTPS as a function of electricity generation during the period analysed. Thus, in order to obtain a clear picture of the corresponding electricity related CO_2, SO_2, NO_X and PM air pollution burden on every station, an integrated method is developed to express the emission production in relation to the amount of electrical energy generated. The values given are expressed in kg of CO_2, SO_2, NO_X or PM emitted per MWh_e of net electricity generated (i.e. gross annual electricity generation minus the self-consumption needs of power stations' auxiliary services). Thus, the emission factor of each LTPS may be generally defined as

$$e_{x_j} = \frac{(m_x)_j}{E_j} \tag{1}$$

where "m_x" are the annual emissions of each air pollutant or GHG under investigation "x" (in this case CO_2, SO_2, NO_X or PM) expressed in kg and "E_j" is the annual net electricity generation (expressed in MWh_e) of the "j" LTPS (see also Table 1).

Proceeding to the results obtained, Figs. 11–15 present the estimated long-term time series and average values (for the period 2005–2011) of the emission factors of CO_2, SO_2, NO_X or PM. Note

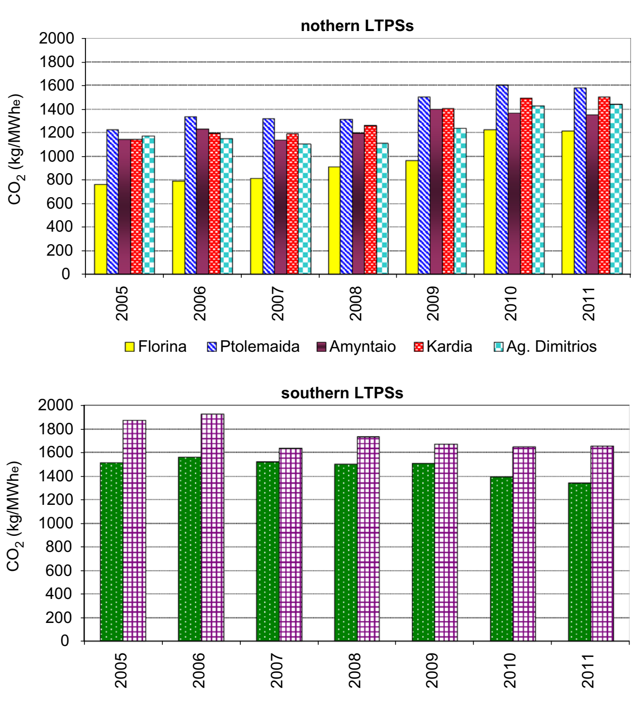

Fig. 11. Long-term time series of CO_2 emission factors for the Greek LTPSs.

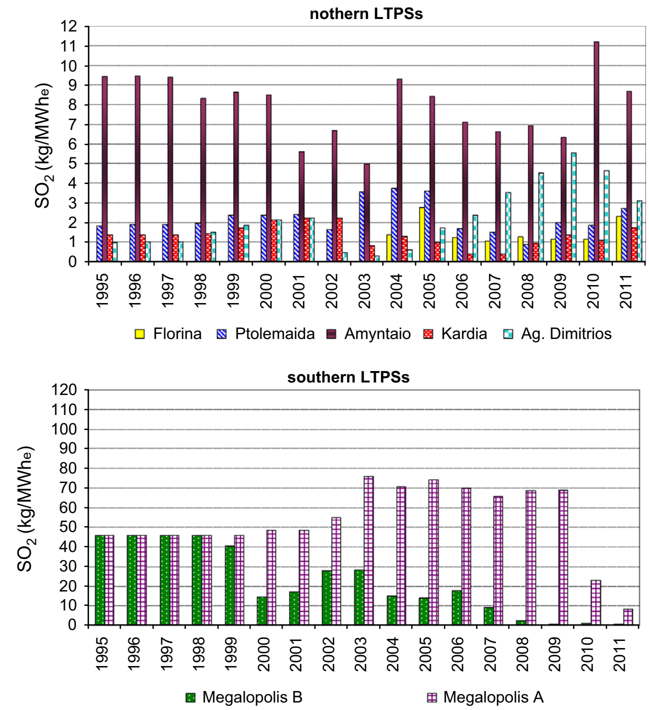

Fig. 12. Long-term time series of SO_2 emission factors for the Greek LTPSs.

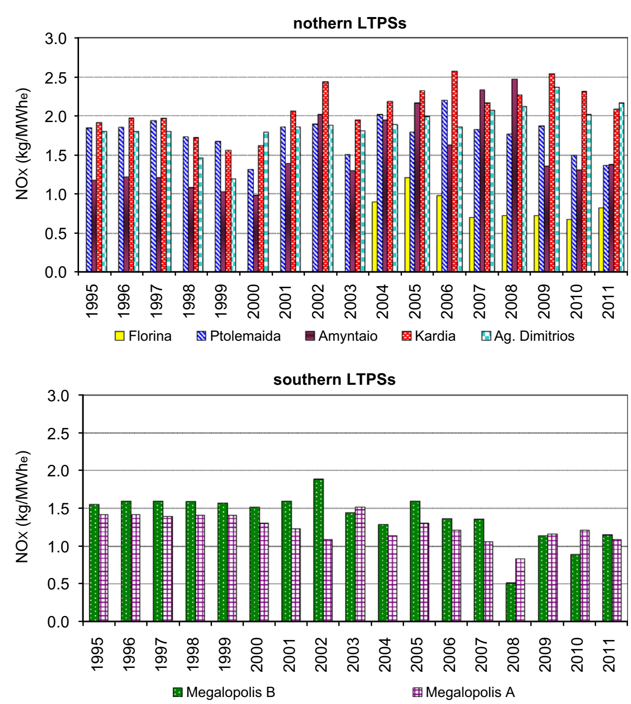

Fig. 13. Long-term time series of NO_X emission factors for the Greek LTPSs.

that the average value depicted in Fig. 15 has been calculated as the ratio of the sum of the emissions (during 2005–2011) from each power station to the sum of the respective energy production, i.e.:

$$\tilde{e}_{x_j} = \frac{\sum (m_{x_j})_i}{\sum (E_j)_i} \tag{2}$$

where "i" represents the respective value for each year (e.g. from 2005 to 2011).

As far as CO_2 emissions are concerned, the highest long-term emission factor values correspond to the southern LTPSs (Fig. 11), fluctuating between 1400 and 1900 kg/MWh$_e$ during the time period analysed (2005–2011). The average emission factor during this time period is about 1500 kg/MWh$_e$ for Megalopolis B power station, while for Megalopolis A thermal plant the respective value reaches almost 1800 kg/MWh$_e$ (see Fig. 15). It is noteworthy though, that during the time period of the 7 years investigated, emission factor values of southern LTPSs remain almost stable (especially for Megalopolis B LTPS), highlighting the limited measures adopted so far in the lignite generation sector for CO_2 emission reduction in compliance with the NAP. Furthermore, the emission factors for the northern LTPSs show a gradual increase (see Fig. 11), with the highest values produced by Ptolemaida's (is the oldest) power station and the lowest by the newest power plant, in Florina.

As it regards SO_2 emissions (Fig. 12), one may see that the values for the northern stations are almost one order of magnitude less than the southern ones for most of the years. In fact, as far as the latter are concerned, the highest emission factor (2005–2011) value corresponds to Megalopolis A power station (see also Fig. 15), which although presented a gradually increasing trend up to 2009, in 2010 decreased significantly (Fig. 12) due to the installation of a flue gas desulphurisation unit. This power plant approached its highest level of approximately 80 kg/MWh$_e$ in 2003 (which corresponds also to the highest SO_2 emission factor recorded from all LTPSs within the investigated time period), while by 2010, the respective amount fell to slightly above 20 kg/MWh$_e$ and even more in 2011 (10 kg/MWh$_e$). Furthermore, as mentioned earlier, the sudden decrease of "$e_{SO2-Megalopolis-B}$" after 1999 was a result of the installation of a desulphurisation unit. It should be noted that before the installation of the desulphurisation unit, this power plant surcharged the environment with approximately 45 kg/MWh$_e$. Nevertheless, that unit faced several operational problems so it did not attribute the maximum benefits that such a system could give, until its upgrading in 2008 which resulted to the low level of about 1 kg of SO_2 per MWh$_e$ generated.

As far as the northern LTPSs are concerned, the highest long-term emission factor value, among the five LTPSs, corresponds to Amyntaio's power plant (exceeding its maximum level of 11 kg/MWh$_e$ in 2010) despite the efforts which were made to restrict SO_2 emissions between 2001 and 2003 (see Fig. 12). Accordingly, one may observe a significant increase – especially during recent years – of the SO_2 emission factor for Agios Dimitrios' thermal power plant (i.e. the first station in terms of capacity and annual energy produced, see also Fig. 15), which reached its highest level of about 5.5 kg/MWh$_e$ in 2009, while in 2011 the respective figure was about 3 kg/MWh$_e$ (Fig. 12). Next is Ptolemaida's and Florina's (i.e. the newest power plant with start-up operation in 2003) TPSs. Note that the sudden increase of the

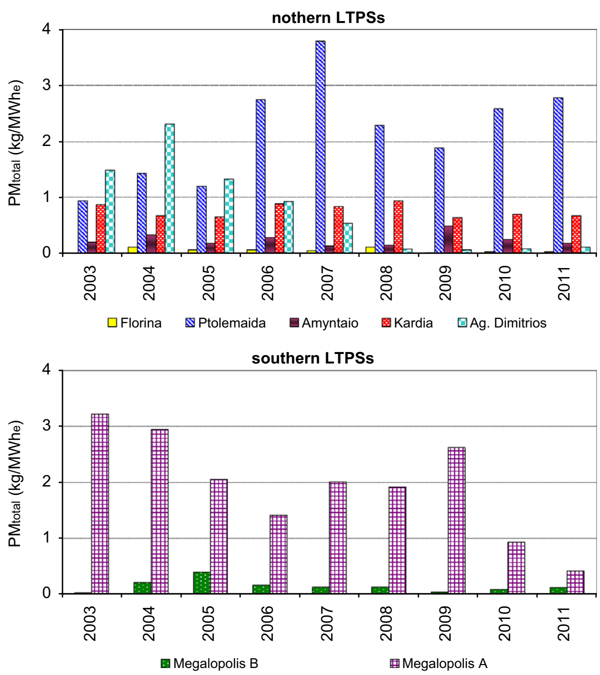

Fig. 14. Long-term time series of PM emission factors for the Greek LTPSs.

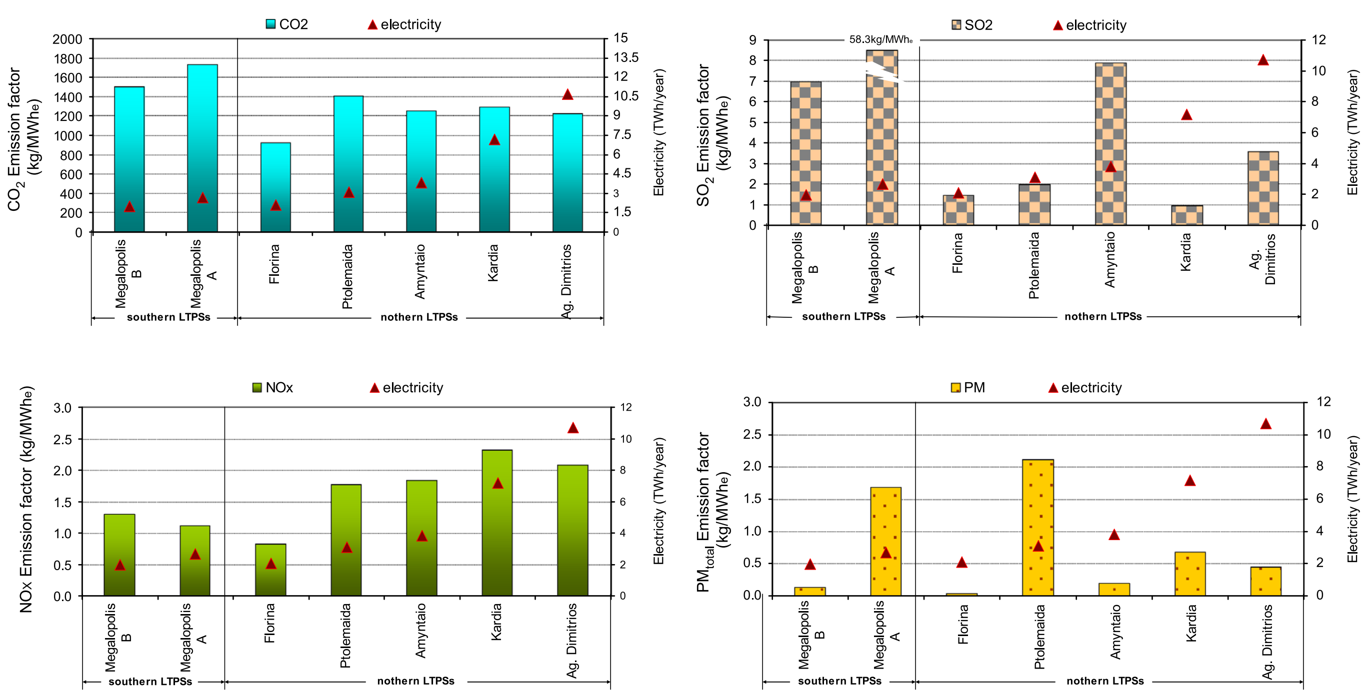

Fig. 15. Average (2005–2011) emission factors and annual electricity generation for each LTPS.

SO_2 emission factor which occurred in 2005 in Florina's power station is owed to a malfunction of the desulphurisation system. Furthermore, the sudden emission factor decrease depicted for the plants of Ptolemaida and Kardia after 2005 is owed to the introduction of higher quality lignite for electricity production.

Subsequently, one may see from Fig. 13 that although there are no huge fluctuations of the annual NO_X emission factors during the time period investigated, a gradual increase takes place after 1999, especially for most of northern Greek LTPSs. The highest value during the period analysed corresponds to Kardia's power station (i.e. the second biggest Greek LTPS in terms of capacity), presenting also the highest average (2005–2011) emission factor, i.e. almost 2.5 kg/MWh$_e$, (see also Fig. 15). Furthermore, substantial emission factors have also been observed for Ptolemaida's and Ag. Dimitrios' LTPSs, both of them reaching their highest values recently, in 2006 and 2009, respectively. Similarly, the Amyntaio's LTPS, following a continuous amplification after 2000, presents rather high emission factor, especially during the recent years (reaching its highest value of 2.5 kg/MWh$_e$ in 2008), while in 2011 the respective amount was slightly below 1.5 kg/MWh$_e$. As far as the two LTPSs of Megalopolis are concerned, one can notice in Fig. 13 a gradual decreasing trend of NO_X emission factors, with most values recorded during the period analysed being below 1.5 kg/MWh$_e$. It should be noted that, the lowest value of NO_X emission factor is achieved by the newest LTPS (in Florina), emitting almost constantly well below 1 kg/MWh$_e$ (see also Fig. 15).

Finally, regarding PM emissions (Fig. 14), the highest long-term emission factor among all LTPSs corresponds to Ptolemaida's power plant with the average value during 2005 and 2011 being almost 2 kg/MWh$_e$. A quite high PM emission factor is also presented by the Megalopolis A power station with the respective average value (2005–2011) being close to 1.5 kg/MWh$_e$ (Fig. 15).

4.2. Evaluation of each LTPS in terms of environmental performance

In addition to the above presented results, one may obtain from Fig. 16 an approximate estimation of the considerable environmental surchage from CO_2, SO_2, NO_X and PM emissions due to lignite combustion for electricity generation. Similarly with the previous figure, the average value for each year depicted in Fig. 16 has been calculated by dividing the sum of the emissions from all power stations with the sum of the respective energy production, i.e.:

$$\tilde{e}_{x_i} = \frac{\sum_{j=1}^{j=6} (m_{x_i})_j}{\sum_{j=1}^{j=6} (E_i)_j} \tag{3}$$

Based on the data depicted, a decreasing rate of average airborne emission factors is not the case (especially for CO_2 and NO_X) during the time period analysed, as a result of the limited implementation – up till now – of effective abatement techniques in the country's lignite-based electricity generation sector. Particularly, regarding CO_2 production, the average annual emission factor fluctuates between 1200 and 1400 kg/MWh$_e$, following a continuous upward trend since 2005. Concerning $NO_{X,}$ the average annual emission factor is found between 1.4 and 2 kg/MWh$_e$, with the highest values being recorded during the last 10 years. On the other hand, the SO_2 emission factor appears to decline, especially after 2010, mainly due to the measures implemented in Megalopolis A power station. Similarly, as far as PM production is concerned, the emission factor fluctuates between 0.5 and 1.4 kg/MWh$_e$, with the lowest value recorded in 2011.

Subsequently, based on the data depicted in Fig. 17, one may say – in rough numbers – that the Greek lignite-based EGS is responsible for the emission of about 8 kg of SO_2, 2 kg of NO_X and 1 kg of PM per MWh$_e$ generated (i.e. average values during 2005–2011). Furthermore, the extremely low calorific value of the Greek lignite (especially that of Megalopolis) and the relatively low efficiency of the thermal power plants result to the very high average CO_2 emission factor value of the order of 1300 kg/MWh$_e$, with the southern LTPSs having the biggest contribution (exceeding 1600 kg/MWh$_e$). In fact, the impact of the Greek lignite on the national CO_2 emissions may also be obtained if it is compared with the respective of other lignites around the world, which, as seen in Fig. 17, range well below 1200 kg of CO_2 per MWh of net electricity generated (and even lower in some other cases) [37,38].

At this point, one may see in Table 2 all the major Greek lignite-fired power stations sorted by the respective average emission

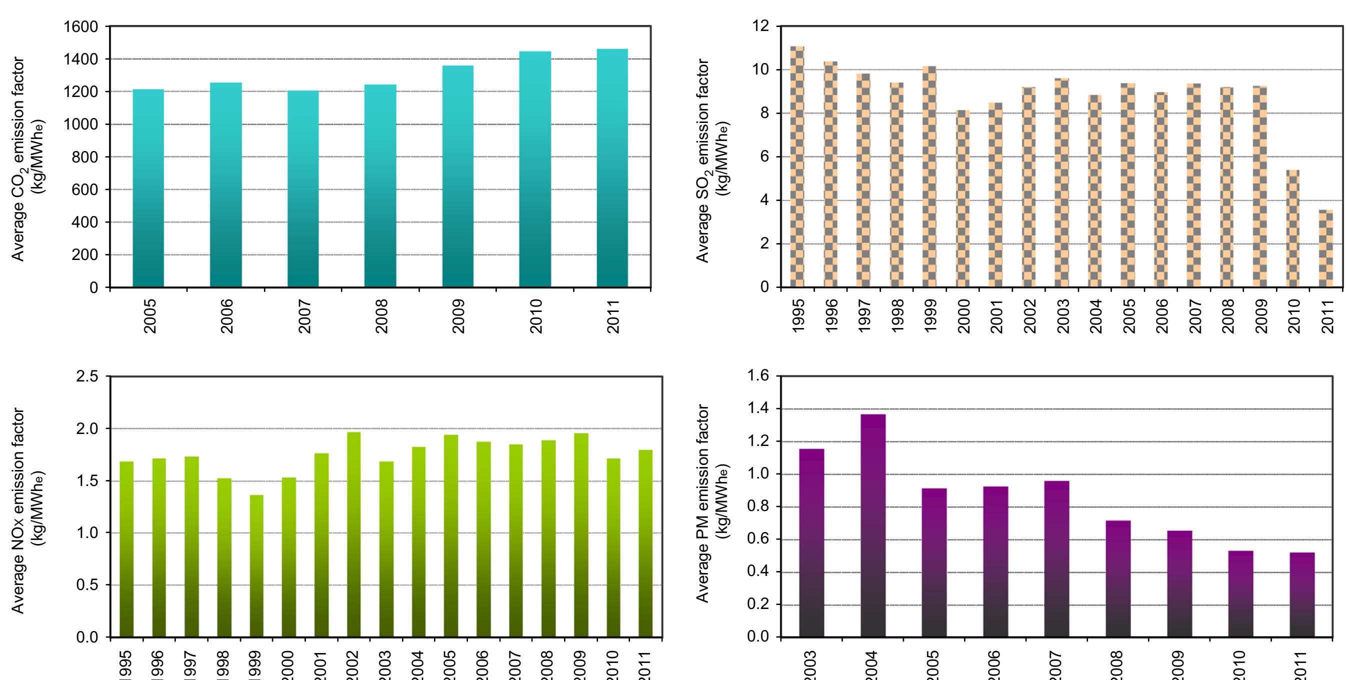

Fig. 16. Average CO_2, SO_2, NO_X and PM emission factors for the Greek lignite-based electricity generation.

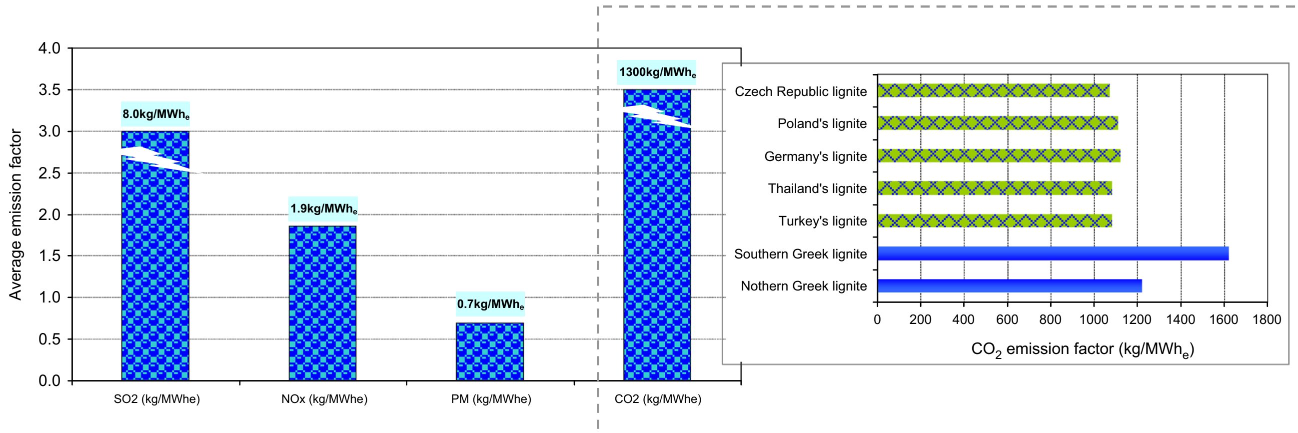

Fig. 17. (Left) Average (2005–2011) of emission factors for the Greek lignite-based electricity generation, (Right) Indicative CO_2 emission factors of several lignite deposits.

Table 2
Lignite-based thermal power stations sorted by their emission factors (kg/MWh_e).

CO_2		SO_2		NO_X		PM	
Plant	**Value**	**Plant**	**Value**	**Plant**	**Value**	**Plant**	**Value**
Emission factors for 2011							
Megalopolis A	1652	Megalopolis A	8.70	Ag. Dimitrios	2.16	Ptolemaida	2.78
Ptolemaida	1577	Amyntaio	8.65	Kardia	2.08	Kardia	0.68
Kardia	1500	Ag. Dimitrios	3.11	Amyntaio	1.37	Megalopolis A	0.42
Ag. Dimitrios	1435	Ptolemaida	2.73	Ptolemaida	1.36	Amyntaio	0.18
Amyntaio	1349	Florina	2.29	Megalopolis B	1.15	Megalopolis B	0.12
Megalopolis B	1340	Kardia	1.73	Megalopolis A	1.09	Ag. Dimitrios	0.10
Florina	1210	Megalopolis B	0.69	Florina	0.82	Florina	0.02
Long-term average (2001–2011)[a]							
Megalopolis A	1733	Megalopolis A	57.14	Kardia	2.26	Ptolemaida	2.18
Megalopolis B	1475	Megalopolis B	12.16	Ag. Dimitrios	2.00	Megalopolis A	1.95
Ptolemaida	1408	Amyntaio	7.44	Ptolemaida	1.78	Ag. Dimitrios	0.77
Kardia	1310	Ag. Dimitrios	2.63	Amyntaio	1.75	Kardia	0.76
Amyntaio	1258	Ptolemaida	2.32	Megalopolis B	1.29	Amyntaio	0.24
Ag. Dimitrios	1232	Kardia	1.22	Megalopolis A	1.17	Megalopolis B	0.14
Florina	952	Florina	1.11	Florina	0.61	Florina	0.05

[a] Note that the long-term average CO_2 emission factor has been calculated from 2005 to 2011, while the long-term average PM emission factor has been calculated from 2003 to 2011.

factors of the last decade as well as the corresponding values recorded in 2011. As already mentioned, the highest values for both CO_2 and SO_2 in 2011 correspond to Megalopolis A power station (1652 and 8.70 kg/MWh_e, respectively). Regarding NO_X emission factors, the highest value corresponds to Kardia's power station, both as long-term average (2001–2011) and highest value (along with Ag. Dimitrios) recorded in 2011 among all power plants (see Table 2). Finally, as for PM pollution levels, Ptolemaida's power station is found responsible for almost 2.8 kg per each MWh_e generated during 2011 (i.e. a value which is about three times higher than the respective figure of the other LTPSs). Furthermore, although Ptolemaida and Megalopolis A TPSs have the worst average long-term (2001–2011) PM emission factor of the whole lignite-based electricity generation sector, the latter station produced in 2011 significantly less than the first one, thanks to the recent introduction of effective filtering technology (see also Fig. 14).

Before concluding, it is also interesting to make a qualitative approach of the impact caused by each LTPS based on grading criteria and the application of various weight factors. Weighing may essentially reflect the relative importance of various factors by assigning more points to the more important factors than the less important ones. Subsequently, the resulting composite indicator value (evaluation grade) may indicate a specific LTPS ranking, being always subject however to a specific judgement. In this context, for the case of LTPSs, assignment of weight factors may be based on several parameters such as environmental impacts, spot market values, political issues, penalties imposed, distribution of allowances, potential health impact and environmental fines for non-compliance with emission standards according to existing air pollution quantification schemes (e.g. the current ETS orders).

Under the above arguments and for the purposes of the current study, the values of the weight factors have been selected by considering the penalties imposed on a LTPS, in case it exceeds the predefined environmental standards and there are not sufficient allowances to cover the excess emissions. In this way, a rough classification of the LTPSs may be made and evaluation grades for each power station may be extracted, based on the corresponding emission factor values. To this end, one may take into account specific weight factors "w_x" on the basis of the fines paid for each excess tonne of CO_2, SO_2, NO_X and PM emitted and estimate the evaluation grades "V" of each LTPS "j" as shown in the following equation.

$$V_j = (e_{CO_2} \cdot w_{CO_2})_j + (e_{SO_2} \cdot w_{SO_2} + e_{NO_X} \cdot w_{NO_X} + e_{PM} \cdot w_{PM})_j \tag{4}$$

Once again, one should clarify that different evaluation results may be obtained using different weight factors in Eq. (4). However, the main contribution of the present study is the long-term

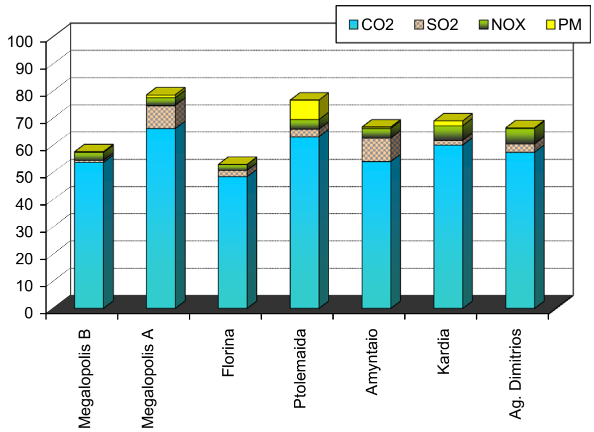

Fig. 18. Qualitative classification of Greek LTPSs on the basis of environmental quantification schemes and emission factors for the year 2011.

estimation of the emission factors of all the LTPS, for the carbon dioxide and for the three basic coal related air pollutants. On top of these, the introduction of the idea of ranking the existing LTPS on the basis of their air pollutants emissions is another innovative point of the proposed study.

According to the results obtained from the above analysis, the worst lignite-fired TPS (in terms of air pollution and climate change) in Greece, as for 2011, is Megalopolis A plant (see Fig. 18) (reaching 80 evaluation grades) mainly due to its severe environmental surcharge caused by the increased SO_2 emissions per MWh_e generated, while the station with the lowest impact is the newest power plant, Florina (having almost 50 grades). Note that for the example case analysed, the respective values have been selected based on the penalties imposed according to the EU's ETS for CO_2 excess ($\sim$100€/t) [39], while weighing of the emission factors of the other pollutants is selected indicatively (i.e. 6500€/t, 2500€/t and 6500€/t), based on common practices applied outside the EU, e.g. US programs designed to control sulphur dioxide under the Clean Air Act (CAA) Amendments and nitrogen oxides under the NO_X Ozone Transport Commission (OTC) [40–42].

5. Conclusions

The carbon dioxide, sulphur dioxide and nitrogen oxides emissions as well particulate matter released by the electricity generation sector up to the year 2011 were analysed in the present study, using detailed official data concerning all the lignite-based TPSs operating in the mainland of Greece.

In Greece, approximately 40% of the annual CO_2 emissions derive from indigenous lignite combustion for electricity production. In this context, although total CO_2 emissions present a slight decreasing trend in the last few years, this reduction cannot be attributed to effective measures adopted in the lignite-based electricity generation sector. In fact, although total CO_2 production from the major LTPSs has been slightly reduced ($\sim$3 Mt) in the last few years (mainly due to electricity demand decrease), the respective emission factors seem to follow an increasing trend since 2005, revealing the limited application – up till now – of drastic measures for CO_2 emission reduction in compliance with the NAP. The highest CO_2 emission factor values correspond to the southern LTPSs, with Megalopolis A power station emitting in 2011 almost 1650 kg of CO_2 per each MWh of electricity generated. Similarly, regarding SO_2 emissions, the contribution of the southern LTPSs is greater mainly due to the low quality of the local lignite used. In fact, the highest emission factor value corresponds again to Megalopolis A power station which although presenting a gradually increasing trend up to 2009, improves its performance significantly after 2010 due to the installation of a flue gas desulphurisation unit. Concerning NO_X emissions factors, the highest recorded values concern Kardia's and Ag. Dimitrios power stations, a fact which makes the results even more important as these LTPSs are the two biggest – in terms of capacity – in Greece, both presenting average capacity factors (or utilisation factors) even higher than 70%. The lowest NO_X emission factor (in the order of 1 kg/MWh_e) corresponds to Florina's power station, reflecting in this way the importance of the age factor in relation to environmental performance when considering such power stations. Finally, regarding PM emissions, the highest emission factor among all LTPSs corresponds to Ptolemaida's power plant, emitting in 2011 almost 3 kg/MWh_e, an amount which is about three times higher than the respective figure of the other LTPSs during the same year.

Accordingly, an innovative evaluation model for the operating LTPSs is developed in the present study, taking into consideration the long-term emission factors for the major air pollutants of these electricity generation installations along with their performance concerning carbon dioxide emissions. The estimated emission factor values may facilitate the local society to rank all the existing LPTSs on the basis of their environmental behaviour and subsequently to define the "worst" or the "best" of these power stations according to the weight factors selected. Besides, the environmental behaviour of the LTPSs may be also considered in the dispatch decision making of the local electricity generation power stations, on top of the techno-economic criteria used up to now.

Synopsizing the present analysis results, one may say that a clear decreasing trend of airborne emission factors is not the case (especially for CO_2 and NO_X) for the time period analysed, underlining the necessity for the implementation of effective abatement techniques in the next few years, in compliance with the country's commitments under the corresponding environmental legislation. In this context, the analysis demonstrated may help decision makers to obtain an idea about the air pollution ranking of the exiting LTPSs and thus to take into account their environmental performance during the daily load demand covering schedule.

Finally, given the importance of the European targets that consider reduction of national emissions, this study lays the foundation for further work of the authors in this field with the view of creating a detailed emission inventory of the overall electricity generation sector in Greece, including emissions from other conventional sources used for electrical energy production.

References

[1] BP. Energy Outlook 2030. Available from: ⟨http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/2030_energy_outlook_booklet.pdf⟩; 2011.
[2] Sakulniyomporn S, Kubaha K, Chullabodhi C. External costs of fossil electricity generation: health-based assessment in Thailand. Renew Sustain Energy Rev 2011;15:3470–9.
[3] Streimikiene D, Roos I, Rekis J. External cost of electricity generation in Baltic States. Renew Sustain Energy Rev 2009;13:863–70.
[4] Río P. Analysing future trends of renewable electricity in the EU in a low-carbon context. Renew Sustain Energy Rev 2001;15:2520–33.
[5] European Association for Coal and Lignite (EURACOAL). Available from: ⟨http://www.euracoal.be/⟩; 2012.
[6] European Commission (EC). The Market for Solid Fuels in the Community in 2009 and Estimates for 2010. Available from: ⟨http://ec.europa.eu/energy/observatory/coal/doc/solid_fuels/2009_report.pdf⟩; 2011.
[7] Tsoutsos T, Papadopoulou E, Katsiri A, Papadopoulos AM. Supporting schemes for renewable energy sources and their impact on reducing the emissions of greenhouse gases in Greece. Renew Sustain Energy Rev 2008;12:1767–88.
[8] Kaldellis JK, Zafirakis D, Kondili E. Contribution of lignite in the Greek electricity generation: review and future prospects. Fuel 2009;88:475–89.
[9] Public Power Corporation (PPC). Available from: ⟨http://www.dei.gr/⟩; 2011.

[10] Konidaris DN. Natural desulfurization in coal-fired units using Greek lignite. Air Waste Management Association 2010;60:1269–73.
[11] Kavouridis K. Lignite industry in Greece within a world context: mining, energy supply and environment. Energy Policy 2008;36:1257–72.
[12] International Energy Agency (IEA). CO2 Emissions from Fuel Combustion. Available from: 〈http://www.iea.org/co2highlights/co2highlights.pdf〉; 2011.
[13] European Environment Agency (EEA). Annual European Union greenhouse gas inventory 1990–2009 and inventory report 2011. Available from: 〈www.eea.europa.eu〉; 2011.
[14] Ministry of Environment, Energy and Climate Change, (MEECC) (former Ministry for the Environment, Physical Planning and Public Works). Annual Inventory Submission under the Convention and the Kyoto Protocol for Greenhouse and other Gases for the Years 1990–2007. Available from: 〈http://www.ypeka.gr〉; 2009.
[15] European Commission (EC)-Eurostat. Available from: 〈http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/〉; 2012.
[16] European Environment Agency (EEA). Greece air pollutant emissions country factsheet, Available from: 〈http://www.eea.europa.eu/themes/air/air-pollutant-emissions-country-factsheets〉; 2012.
[17] Ministry of Environment, Energy and Climate Change (MEECC) (former Ministry for the Environment, Physical Planning and Public Works). Informative inventory report-submitted under the convention on long-range transboundary air pollution. Available from: 〈http://www.ypeka.gr〉.; 2013.
[18] Paliatsos AG, Kaldellis JK, Koronakis PS, Garofalakis JE. Fifteen year air quality trends associated with the vehicle traffic in Athens, Greece. Fresenius Environ Bull 2002;11/12b:1119–26.
[19] Nastos PT, Paliatsos AG, Anthracopoulos MB, Roma ES, Priftis KN. Outdoor particulate matter and childhood asthma admissions in Athens, Greece: a time-series study. Environmental health 2010;9:45.
[20] Kopanakis I, Lazaridis M, Lydakis Simantiris N, Katsivela E, Eleftheriadis K, Pentari D., et al. Particulate matter size distribution measurements at Akrotiri Station, Crete, Greece. In: Proceedings of the international conference on the protection and restoration of the environment IX, Kefalonia, Greece, June 29–July 3; 2008.
[21] Dimitroulopoulou C, Plemmenos V, Ziomas I. Air Pollution. Energy-related particulate matter emissions (EEA EN07). Available from: 〈http://62.217.124.156/images/stories/indicators/AirPollution/Drivers/EEA-GR-EN07.pdf〉; 2009.
[22] European Environment Agency (EEA). EN07 Energy-related particulate matter emissions. Available from: 〈http://www.eea.europa.eu/data-and-maps/〉; 2012.
[23] Chaloulakou A, Kassomenos P, Spyrellis N, Demokritou P, Koutrakis P. Measurements of PM_{10} and $PM_{2.5}$ particle concentrations in Athens, Greece. Atmos Environ 2003;37:649–60.
[24] Gerasopoulos E, Kouvarakis G, Babasakalis P, Vrekoussis M, Putaud JP, Mihalopoulos N. Origin and variability of particulate matter (PM_{10}) mass concentrations over the Eastern Mediterranean. Atmos Environ 2006;40:4679–90.
[25] Grivas G, Chaloulakou A, Kassomenos P. An overview of the PM10 pollution problem, in the Metropolitan area of Athens, Greece. Assessment of controlling factors and potential impact of long range transport. Sci Total Environ 2008;389:165–77.
[26] Triantafillou AG, Paliatsos AG, Antoniou A, Viras LG, Evagelopoulos V. PM_{10} concentration levels in different areas of Greece. In: Proceedings of the eighth panhellenic conference in meteorology, climatology and atmospheric physics, Athens, Greece; 2006.
[27] Markakis K, Poupkou A, Melas D, Zerefos C. A GIS based anthropogenic PM_{10} emission inventory for Greece. Atmos Pollut Res 2010;1:71–81.
[28] Kaldellis JK, Mantelis N, Zafirakis D. Evaluating the ability of Greek power stations to comply with the obligations posed by the second National Allocation Plan concerning carbon dioxide emissions. Fuel 2011;90:2884–95.
[29] European Commission (EC). Verified Emissions for 2008-2009-2010-2011 and allocations 2008-2009-2010-2011. Available from: 〈http://ec.europa.eu/〉; 2013.
[30] Kaldellis JK, Spyropoulos G, Chalvatzis KJ. The impact of Greek electricity generation sector on the national air pollution problem. Fresenius Environ Bull 2004;13:647–56.
[31] Kaldellis JK, Voutsinas M, Paliatsos AG, Koronakis PS. Temporal evolution of the sulphur oxides emissions from the Greek electricity generation sector. Environ Technol 2004;25:1371–84.
[32] Public Power Corporation (PPC). Annual reports of thermal power stations 2003-2011, Observation on environmental parameters of operation (in Greek); 2011.
[33] Public Power Corporation (PPC). Sustainable development plan. Available from: 〈http://www.dei.gr/Documents/PERIV.gr.oct_09.pdf〉.; 2009.
[34] Kaldellis JK, Vlachos GTh, Paliatsos AG, Kondili E. Detailed examination of the Greek electricity sector nitrogen oxides emissions for the period 1995–2002. Environ Sci Policy 2005;8:502–14.
[35] Ghose MK, Majee SR. Assessment of dust generation due to opencast coal mining – an Indian case study. Environ Monitor Assess 2000;61:255–63.
[36] Triantafyllou AG. Patterns and concentrations of PM_{10} in a mountainous basin region. J Air Waste Manage Assoc 2000;50:1017–22.
[37] Ari I, Koksal MA. Carbon dioxide emission from the Turkish electricity sector and its mitigation options. Energy Policy 2011;39:6120–35.
[38] Krittayakasem P, Patumsawad S, Garivait S. Emission inventory of electricity generation in Thailand. J Sustain Energy Environ 2011;2:65–9.
[39] European Commission (EC). The EU emissions trading scheme. Available from: 〈http://ec.europa.eu/clima/publications/docs/ets_en.pdf〉; 2009.
[40] Kenney R.Gastman A., Clean Air Act, United States. Available from: 〈http://www.eoearth.org/article/Clean_Air_Act,_United_States〉; 2010.
[41] Garcia C. San Joaquin Valley unified air pollution control district Draft Staff Report. Draft Amendments to Rule 3170 (Federally Mandated Ozone Nonattainment Fee). Available from: 〈http://www.valleyair.org/workshops/postings/2011/3-8-11-rule3170/Draft_Staff_Report_3170_%203-8-2011.pdf〉; 2011.
[42] Environmental Protection Agency (EPA) U.S. Allowance Markets Assessment: a closer look at the two biggest price changes in the federal SO_2 and NO_X allowance markets. Available from: 〈http://www.epa.gov/airmarkets/resource/docs/marketassessmnt.pdf〉; 2009.